Hydrogen Maser Research and Development
at Sigma Tau Standards
and Tests of Sigma Tau Masers at
the Naval Research Laboratory

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INTRODUCTION

Two hydrogen masers of the active oscillator type using automatic cavity stabilization, but without active feedback gain, were designed, built and tested by Sigma Tau Standards for the Naval Research Laboratory (NRL). The masers were tested at Sigma Tau Standards prior to shipment and again at the NRL for a period of ten weeks following delivery. In addition, Sigma Tau has modified a Small Hydrogen Maser previously built to operate with cavity feedback to become an oscillating maser without feedback.

MASER DESIGN

The primary purpose of NRL's purchase of the two Sigma Tau Masers was to evaluate the long term stability of a hydrogen maser using the modulated cavity servo system developed by Sigma Tau. The design has been previously described [1,2] and will only be summarized here. The masers use a high-Q cavity with a thin quartz tube to provide dielectric loading and thus some reduction in cavity size as compared with previous oscillating hydrogen masers. Four magnetic shields are used. The state selector is a quadrupole assembly developed and manufactured by Sigma Tau. Both masers are designed to operate on either 115 VAC or 28 VDC and

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **DEC 1985**	2. REPORT TYPE	3. DATES COVERED **00-00-1985 to 00-00-1985**

4. TITLE AND SUBTITLE **Hydrogen Maser Research and Development at Sigma Tau Standards and Tests of Sigma Tau Masers at the Naval Research Laboratory**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,4555 Overlook Ave SW,Washington,DC,20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Proceedings of the Seventeenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, Washington, DC, 3-5 Dec 1985

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**24**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

came equipped with a battery backup and an automatic charging system.

The cavity control circuit uses modulation of the cavity frequency about the nominal center tuning point to determine any cavity mistuning. The frequency of the cavity is alternately stepped between two tuning points which are equally and oppositely spaced about the center. The maser output signal amplitude is then synchronously detected with the modulating signal to determine the magnitude and direction of the mistuning. When the cavity is perfectly aligned, the amplitude modulation of the output signal is nulled. As will be shown in the phase noise measurements, the effect on the output signal at 5 MHz is 100 db below the carrier.

TESTING

The goal of the testing program at NRL was to measure the normal operating performance of the clocks, with particular attention being given to the long term drift. Measurements were made of short term stability, phase noise, IF signal level, ion pump loading and frequency drift with respect to the U.S. Naval Observatory (USNO). All tests were performed at NRL in a laboratory environment. These results were compared with the data that were taken at Sigma Tau prior to shipment. No drift was removed in any subsequent calculation.

The masers were delivered to NRL by the manufacturer under power for ion pump operation only. No problems were noted in delivery. Warm up time for the masers to achieve temperature stability and oscillation was 1 day for maser serial number N1 and about three days for maser number N2. The difference in warm up is due to a deliberate design difference in the thermal control systems of the two units. Both were operated on unconditioned 117 VAC power

in a laboratory environment. Temperature control was on the order of two degrees C peak to peak. There was one air conditioning failure during the test period.

Short-term stability tests were performed using the 100 MHz outputs into a single mixer with one maser offset by approximately 1 Hz. The masers were measured against each other and also against NRL's house standard VLG-11 hydrogen maser (serial number P12). For measurements with averaging times greater than 1000 seconds, NRL's long-term data system was used. The long term system uses multichannel dual-mixer technology and allows measurements of up to 48 clocks simultaneously [3]. Data were taken at Sigma Tau using a single mixer prior to shipment and the results are shown in Fig. 1. This analysis assumes equality of the two clocks under test and thus includes division by the square root of two. Figures 2, 3 and 4 show the results of the NRL tests. The NRL computations do not assume equality.

The measured performance of the three clock pairs was very close for measurement times from 1 second through 1000 seconds. The measurements taken for averages of 2000 and 4000 seconds using maser N2 show a marked increase in noise as compared with the data taken with the single mixer system at 1000 seconds. This is apparently a measurement artifact due to the nature of the measurement system and the operating frequency of the cavity control servo system of the maser. The cavity modulation frequency of maser N2 is 20 Hz and, as will be seen in the following discussion on phase noise, there are sidebands at that frequency. The offset frequency used in the dual-mixer measurement system is 10 Hz. Thus, the N2 maser has a spurious output in the dual mixer system at the nominal beat frequency of the measurement. A subsequent repeat of the single-mixer test confirmed that the data shown in Fig. 1 and 2 for maser N2 had not degraded.

PHASE NOISE

Phase noise measurements were made using the 5 MHz outputs. For this measurement, the maser synthesizers were adjusted to provide essentially zero offset for the period of the measurement. No phase-lock techniques were used. Figure 5 shows the close-in phase noise for maser N1 vs N2. The peak at about 3 Hz offset from the carrier is due to the loop bandwidth of the maser crystal control loops. The peaks at 20 and 25 Hz are due to the cavity control modulation for N2 and N1 respectively. The 60 and 75 Hz responses are the third harmonics of the square wave modulation.

Figure 6 is a plot of the phase noise of the same clocks covering the frequency range out to 100 kHz. The largest discrete noise source is due to IF feedthrough in maser N2 at 5.751 kHz and its odd harmonics. The remaining peaks seem to be related to power supply switching frequencies leaking through to the RF outputs. As a way of identifying which of the two masers was responsible for the spurious outputs, the same tests were run using the VLG-11 maser as a reference. Figures 7 and 8 are for maser N1 and Figs. 9 and 10 show N2. Using these three points of comparison, the conclusion is that IF feedthrough and power supply noise are primarily in maser N2. It should be noted that the phase noise of the early VLG-11 masers, including P12, is quite poor within 100 Hz of the carrier due to the crystal oscillator. The power supply leakage at about 16 kHz is in maser P12.

FREQUENCY DRIFT

One of the major factors limiting the use of active hydrogen masers as clocks for long-term timekeeping has been frequency drift. NRL's experience with VLG-10 and VLG-11 masers has shown drift rates of just less than 1×10^{-14} per day. Since the Sigma

Tau masers included a continously operating cavity frequency control servo, a measurement of such drift is very significant. In order to determine the drift, several measurement techniques were used. Each Sigma Tau clock was measured on the long-term dual-mixer system over a period of about 6 weeks against each other, the VLG-11 and NRL's house cesium clock (HP 5061/004). Measurements were also made against the U.S. Naval Observatory (USNO) Master Clock. Relative time measurements were made against USNO using the carrier of television station WTTG as a common phase reference [4,5]. GPS common-view measurements were made using a single-frequency time-transfer receiver and the data published by USNO to verify the television method.

Figure 11 shows the phase of the Sigma Tau masers relative to each other. For the span shown, the drift rate between the two is just less than 1×10^{-14} per day. To determine the source of the drift, each maser was referenced to the cesium standard, Fig. 12. This showed a possible drift in maser N2 and an apparent frequency jump in either N1 or the cesium. Figure 13 plots the frequency offset of each clock with P12 as a reference, confirming that the frequency jump in the previous figure must have been in the cesium and not in the maser N1. Figures 14 and 15 show the phase comparisons to USNO for masers N1 and N2 respectively. Figure 16 verifies the TV comparison method, showing NRL's cesium with respect to USNO by both methods. The television time comparison with USNO clearly shows that significant drift is present in maser N2. There is no clearly discernible drift in the N1 data, and a linear fit to the frequency showed less than 1×10^{-15} per day drift. A fit of the N2 data indicates an average drift rate of about -7×10^{-15} per day for the period.

Readings of the analog monitors of various maser operating parameters were taken several times during the test period. The

available monitors include oven voltages, servo loop parameters, power supply voltages, and pump currents. Only a few showed significant changes over the period of the test. Of these, the maser output power as shown by the signal level in the receiver IF, Fig. 17, and the cavity tuning register in Fig. 18 show correlation to the frequency drift for maser N2. Ion pump currents in both masers were stable for the entire test period with currents no more than 50 microamps. There were no indications of any other abnormalities in the maser physics units.

OPERATION

Another major concern in the use of hydrogen masers is the difficulty of operation in terms of special requirements for sites, maintenance, and reliability. As described earlier, these masers have been operated in a normal laboratory space. Their size and weight are sufficiently small so as to allow movement within the laboratory easily.

For the period covered by this report, there were no observed failures. There was one change in performance. Maser N1 experienced a large jump in the crystal oscillator control voltage 3 weeks into the test, as shown in Fig. 19. The offset and stability of N1 were not affected. Based on subsequent measurements, it was determined that this large change was due to a change in the crystal oscillator oven temperature which occurred over a period considerably longer than the maser loop time constant. Although there was no deterioration in laboratory performance, the oscillator will be replaced.

In order to be able to measure maser N2 accurately on the long term data system, the cavity servo modulation frequency will be

changed slightly to avoid the spurious 10 Hz beat note. No other maintenance has been required.

SMALL HYDROGEN MASER

During the past year at Sigma Tau Standards the analysis of maser cavity structures has been extended to establish the smallest practical active oscillator cavity assembly using quartz dielectric loading. Experimental tests of one small assembly in an operational maser has been successfully carried out and confirms the theoretical analysis and also demonstrates that a relatively small, self oscillating, atomic hydrogen maser is indeed feasible.

The test bed for the new small cavity assembly was the Small Hydrogen Maser (SHM) previously developed for the United States Air Force which used electrodes surrounding the maser storage bulb to reduce the cavity size. The original SHM required active cavity gain to oscillate and the relatively poor performance achieved with this technique was reported [6]. Figure 20 is a picture of the SHM illustrating the small size and compact packaging of this maser. Figure 21 is a drawing showing the new cavity configuration upon which the new work reported here is based. There is an elongated copper cavity with a very heavy wall quartz atom storage bulb within a close fitting quartz cylinder. The bulb is fastened to the cylinder with three thin quartz shims on each end using thin layers of high vacuum epoxy as an adhesive. There is a thin layer of teflon between the quartz cylinder ends and the cavity ends for thermal expansion relief, and spring tension from the cavity end plates make a very rigid structure.

The inside dimensions of the original SHM cavity were 7.73 cm (6.09 inches) diameter by 22.86 cm (9 inches) long. As discussed

in reference [2], the most important factor in establishing whether a particular hydrogen maser is a practical self oscillator is the product of filling factor (n') times cavity quality factor (Q). Computations have been made for a variety of cavities of differing lengths, bulb sizes, dielectric loading amount and cavity radius at resonance. Figure 22 illustrates the results for one particularly promising combination of cavity and bulb length and bulb inside diameter and shows the variation of $n' \times Q$ and cavity radius as the thickness of the quartz dielectric is varied.

It was established from the analysis that one feasible configuration would fit within the copper cavity originally used in the SHM. This is shown in the lower dotted lines in Fig. 22. Parts with the dimensions indicated were procured, the bulb coated with teflon, and the cavity assembled and tuned with the following results.

Q_1 = 27,300 (Loaded Q)

B = .062 (Coupling Coefficient)

Q_o = 29,000 (Unloaded Q)

n' = .38 (Calculated)

$n' \times Q_o$ = 11,070 (Using Experimental Q_o).

The calculated Q_o for this geometry was 30,544 giving

$n' \times Q_o$ = 11,607 (Calculated)

This is within the experimental error due to the approximations made in the analysis. The calculated cavity diameter was also in good agreement with the experimental diameter and the new quartz cylinder and bulb assembly fit neatly into the original SHM copper cavity.

The SHM has been reassembled using the new configuration and it is found that the maser oscillated reliably with relatively low flux (.04 moles of H_2 per year.) This is not as efficient as the larger Sigma Tau masers (.01 moles H_2 per year) but is excellent in relation to early maser designs and would give a hydrogen pump lifetime estimated as over 5 years using a 20 liter per second sputter ion pump.

The product of n' x Q indicated in Fig. 22 for the SHM is nearly the minimum for a reliable maser oscillator, and the new SHM experiment has been carried out primarily to establish the concreteness of the analysis and design concepts. For example, the product n' x Q for the large Sigma Tau (NRL) masers is well over 25,000 in comparison to the 11,600 for the SHM. The factors and dimensions for a better design than the present implementation of the SHM is also indicated in Fig. 22. This "improved design" would have a much lower threshold for the oscillation and better efficiency, yet the cavity is still quite small, only 17.15 cm (6.75 inches) diameter.

Limited testing of the SHM was done at NRL in conjunction with the tests of the two larger masers. It was found that the SHM required strong magnetic field settings in order to oscillate. The high field should result in increased sensitivity to external fields and limit stability. The magnetic problem was due to construction problems and is not inherent to small maser design. Data showing Allan Variance for averaging times of 1 second to 1000 seconds were taken using maser N1 as a reference, Fig. 23.

CONCLUSIONS

The two Sigma Tau masers delivered to NRL are working without major problems. The performance of maser N1 is very good with no measureable drift and good active maser short term stability.

Maser N2 is nearly as good but does show long term drift similar to other active masers. Sigma Tau Standards believes that some improvement will occur with longer periods of operation. Maser N1 was built about 1 year prior to N2 and also showed initial decays in IF level. The Small Hydrogen Maser did show the type of performance one would expect from a maser with a lightly coupled cavity. The flicker floor apparently reached at 100 seconds is probably due to the high sensitivity to magnetic field.

ACKNOWLEDGEMENTS

The NRL authors wish to thank Mr. Alick Frank of NRL for his assistance in setting up and conducting the experiments reported here. They also acknowledge WTTG Television in Washington for their support and assistance in the installation and operation of the television time transfer equipment.

Sigma Tau standards wishes to recognize the government contracts which supported the maser development reported here. The Light-Weight Hydrogen Maser effort (Small Hydrogen Maser) was sponsored by the Deputy for Electronic Technology (RADC/ET), Air Force Systems Command, under contract number F19628-79-C-104. The NRL maser development and procurement was supported by the Naval Research Laboratory under contract N00014-83-C-2015.

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3. S.R. Stein and G.A. Gifford, "Software for Two Measurement Systems," Proceedings, 38th Annual Symposium on Frequecny Control, 1984.

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5. To be published.

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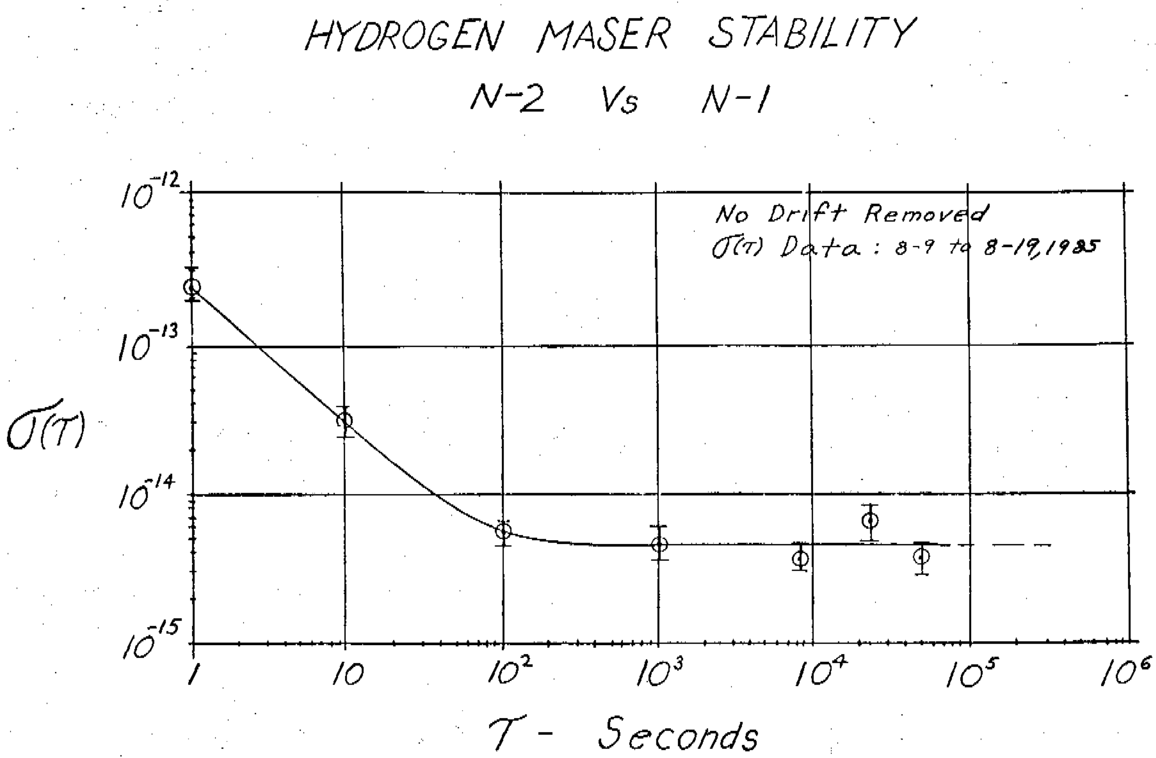

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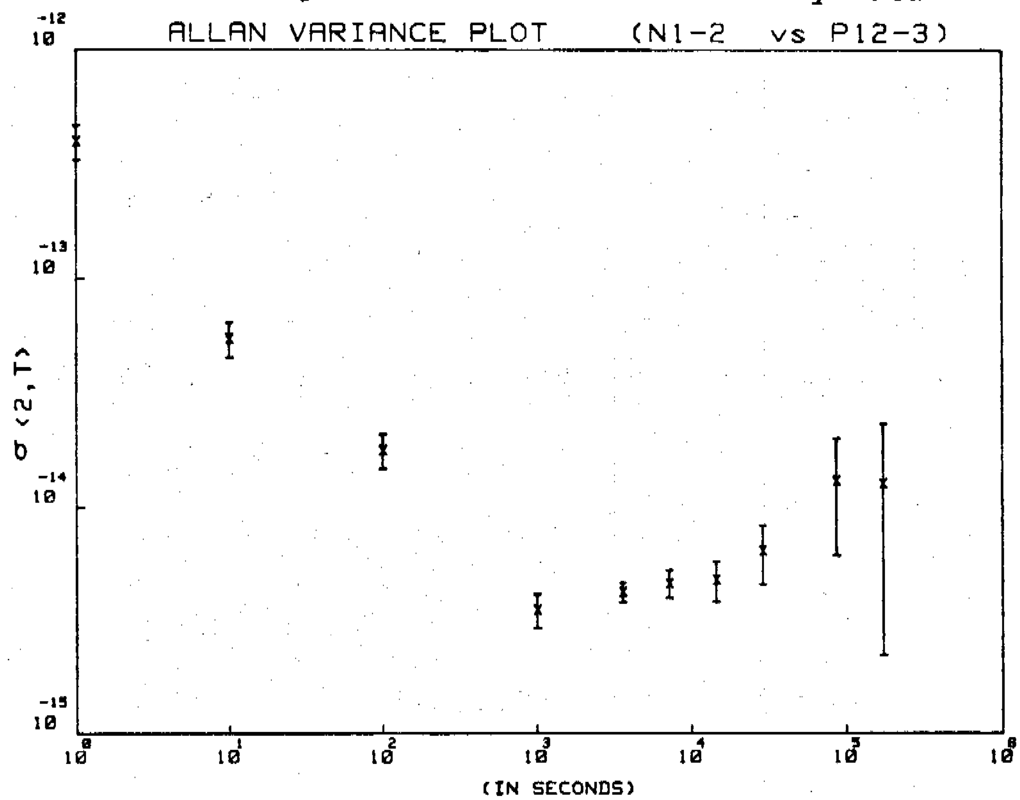
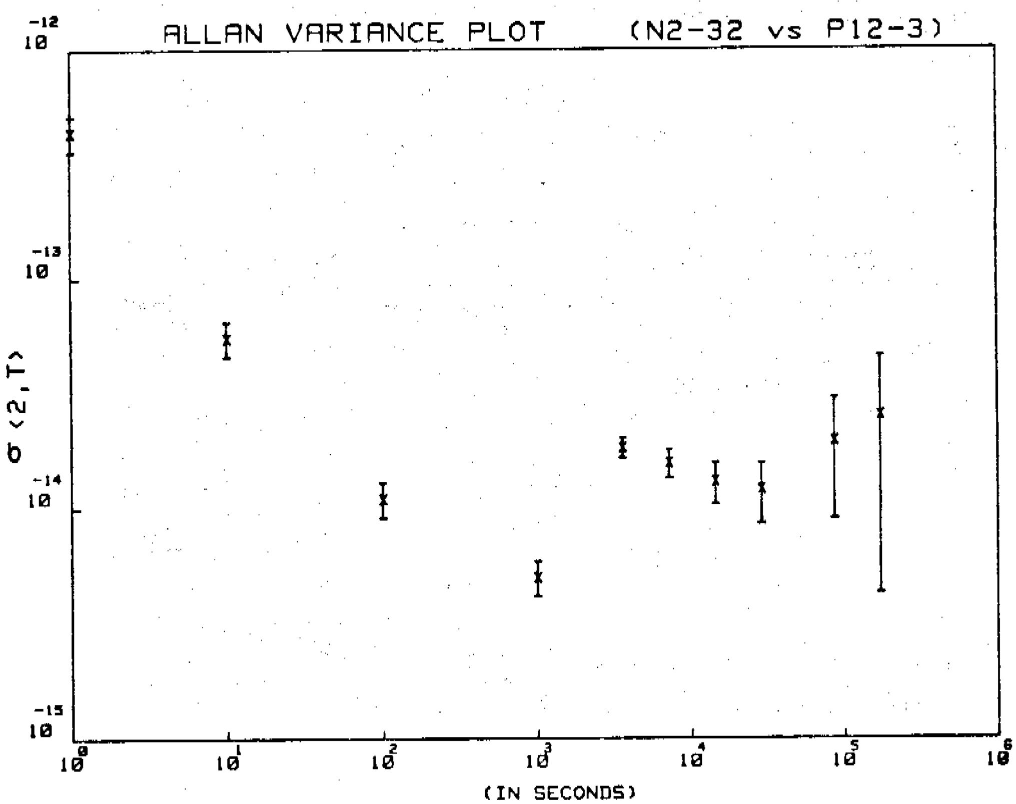
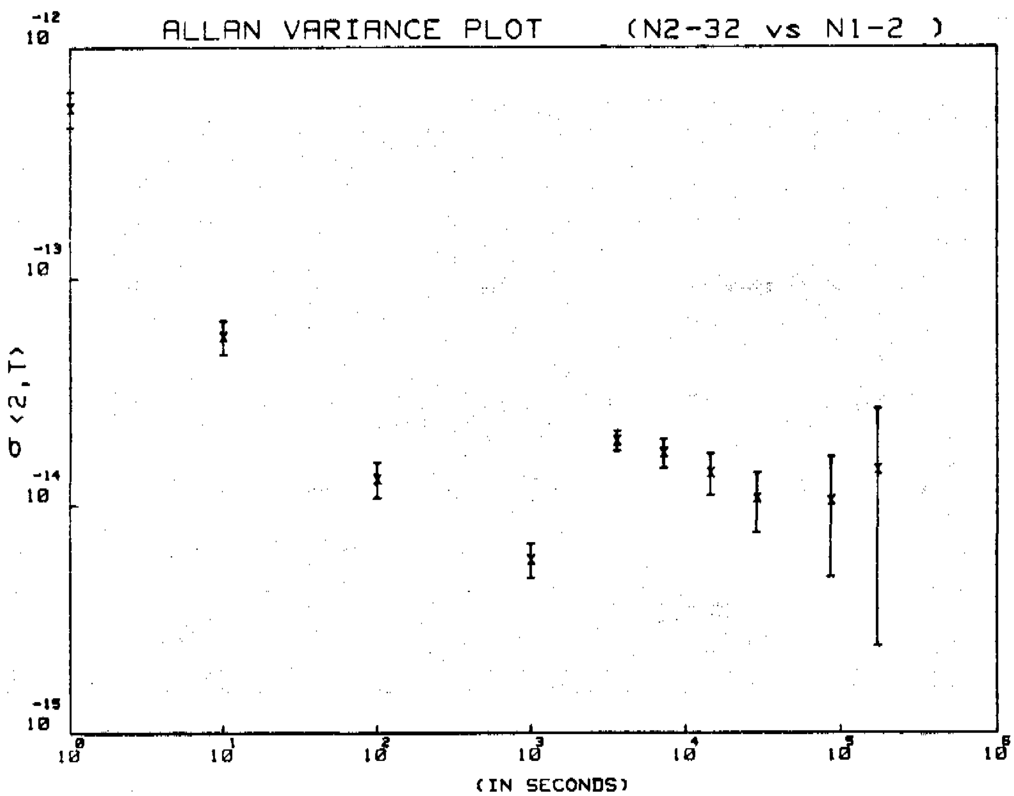


2. **NRL Allan Variance Data, N1 vs P12**



3 NRL Allan Variance Data, N2 vs P12



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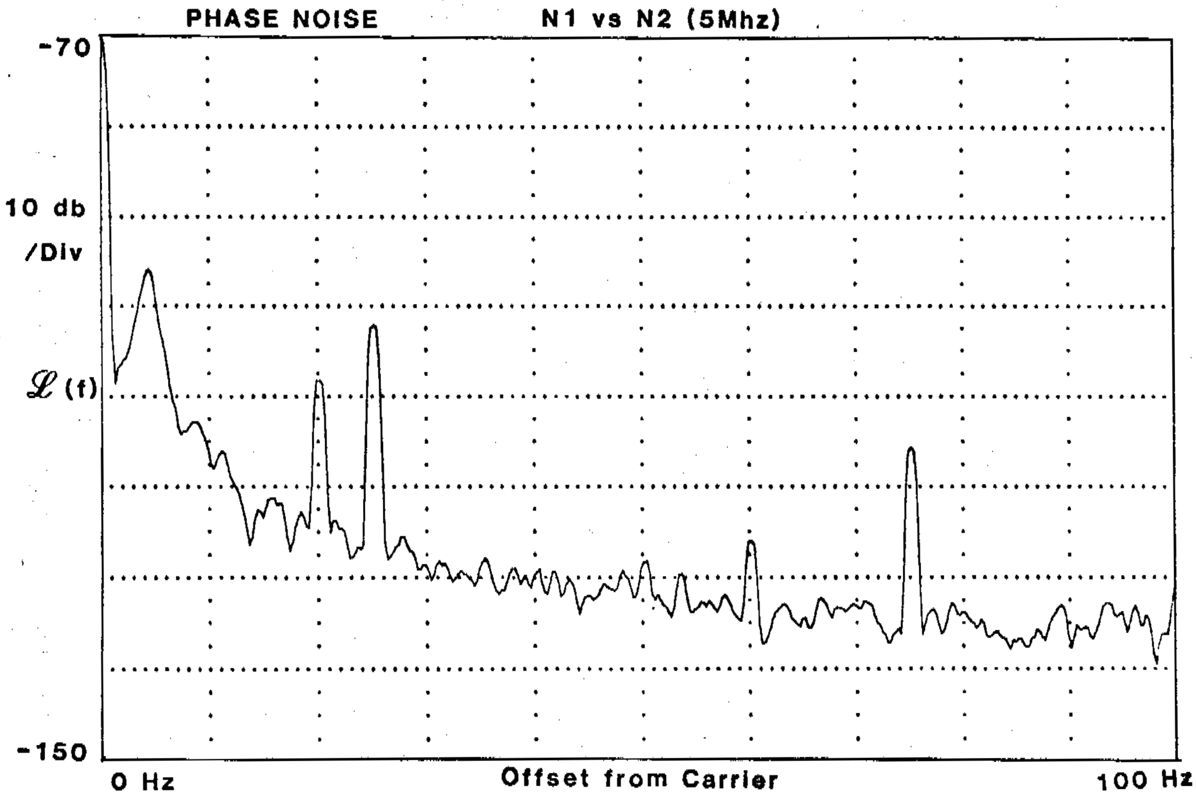
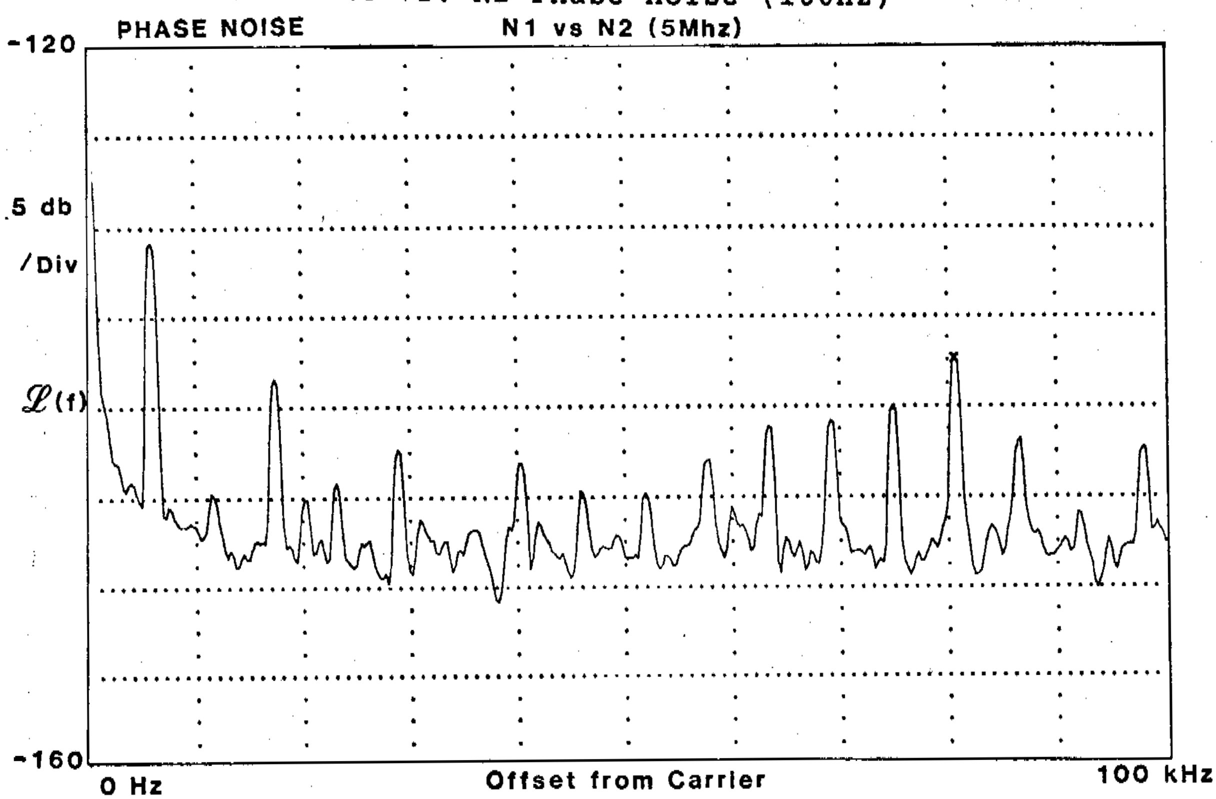
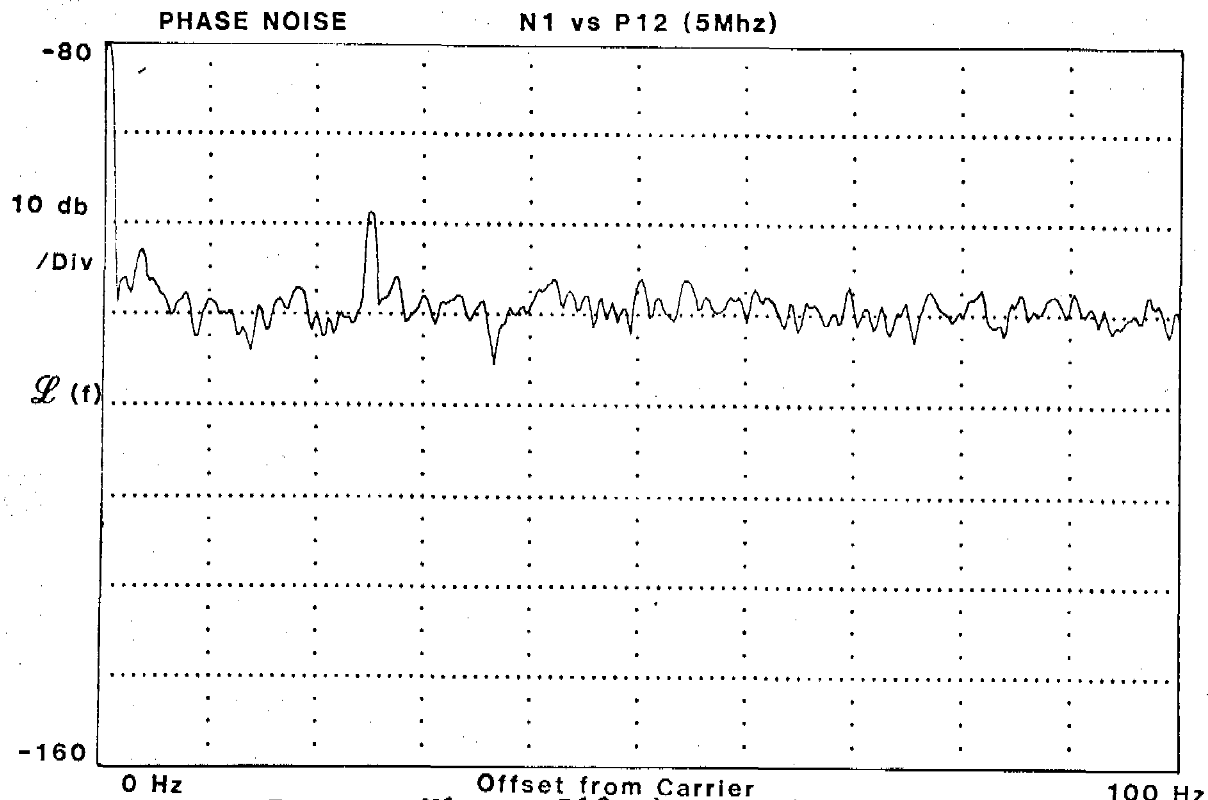


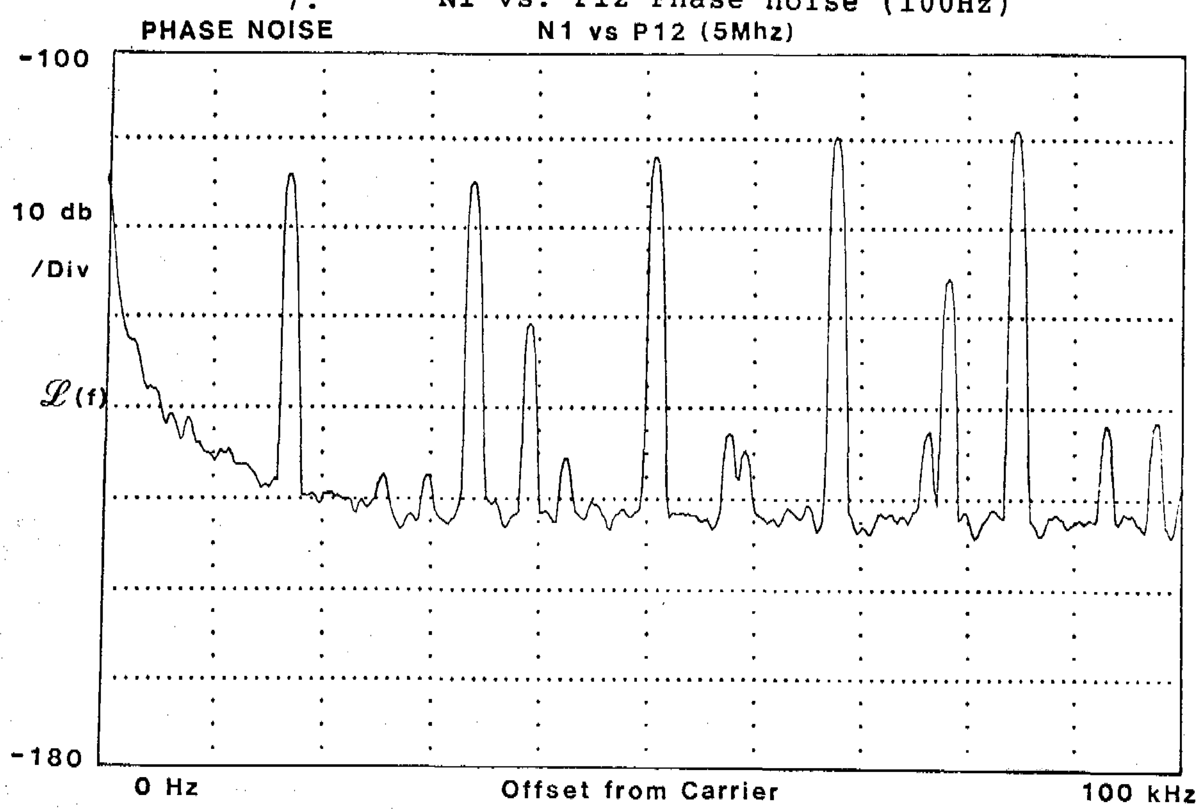
5. N1 vs. N2 Phase noise (100Hz)



6. N1 vs. N2 Phase noise (100kHz)



7. N1 vs. P12 Phase noise (100Hz)



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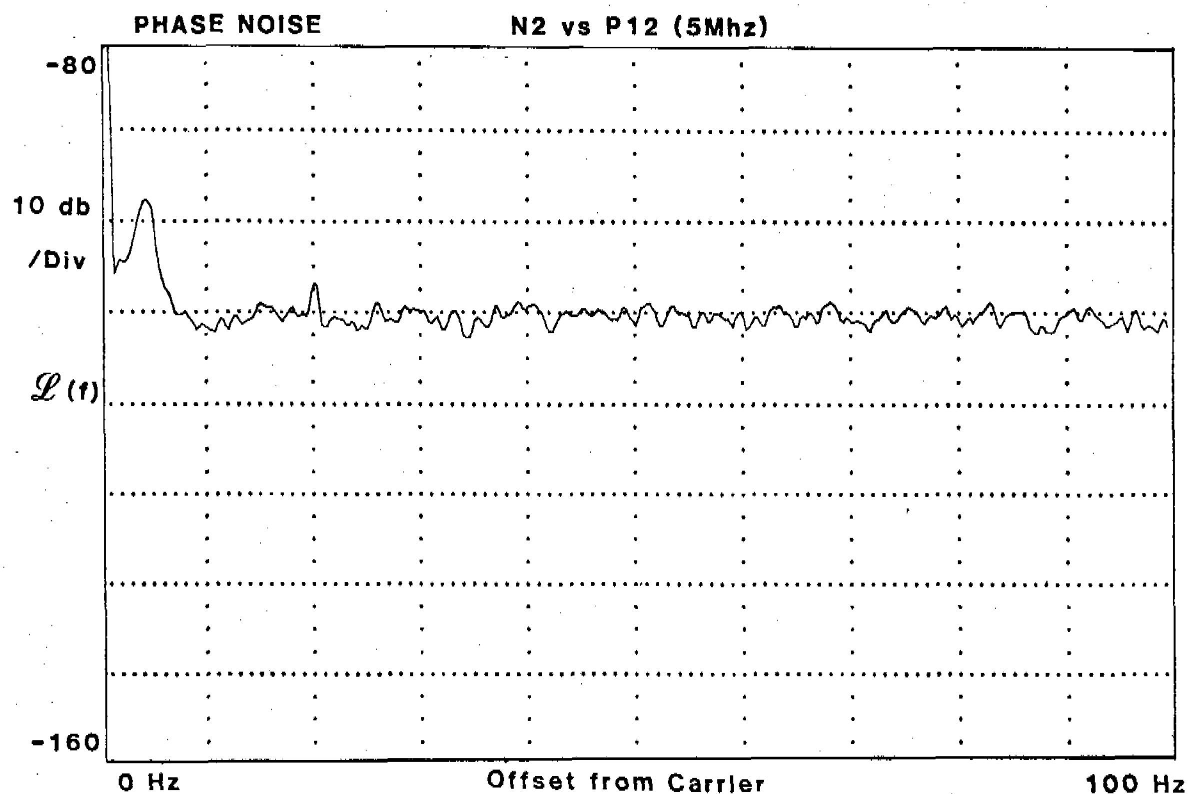
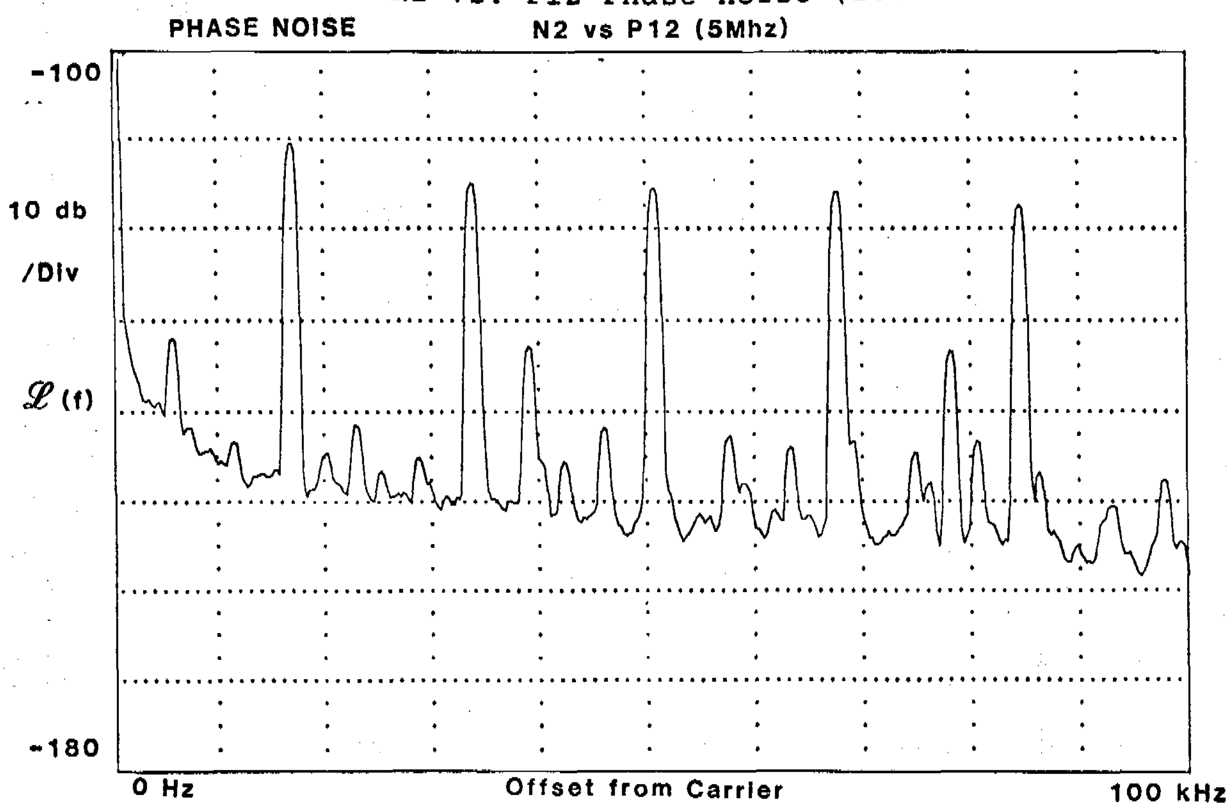
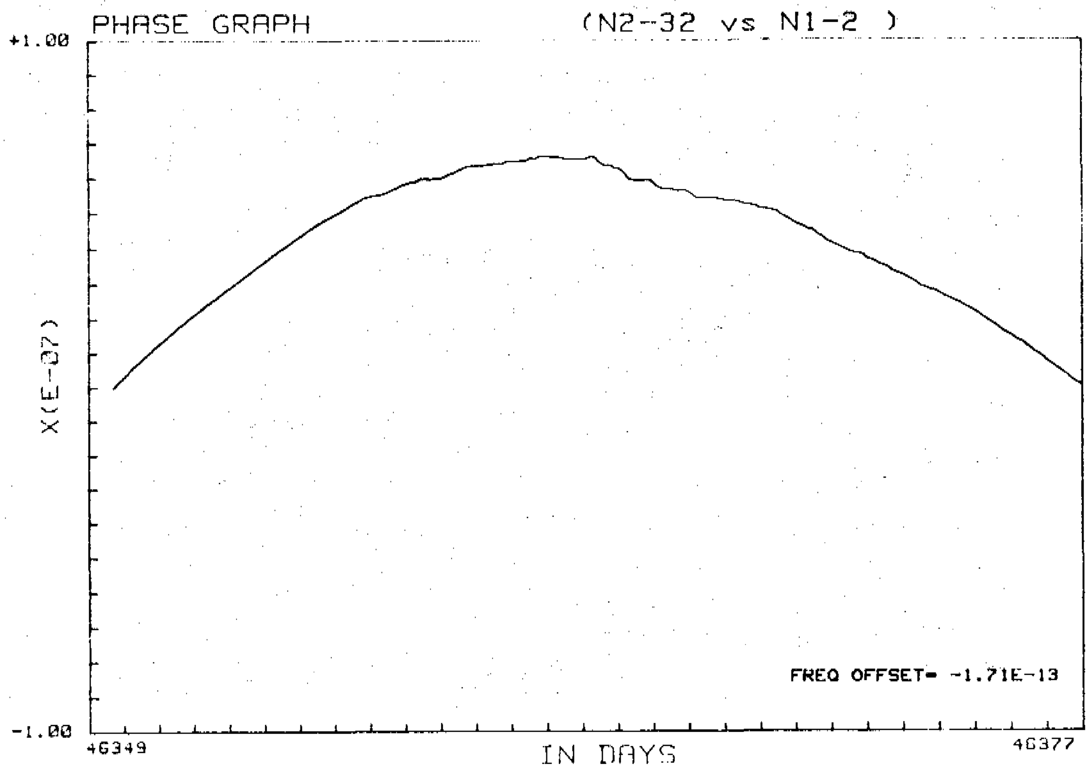


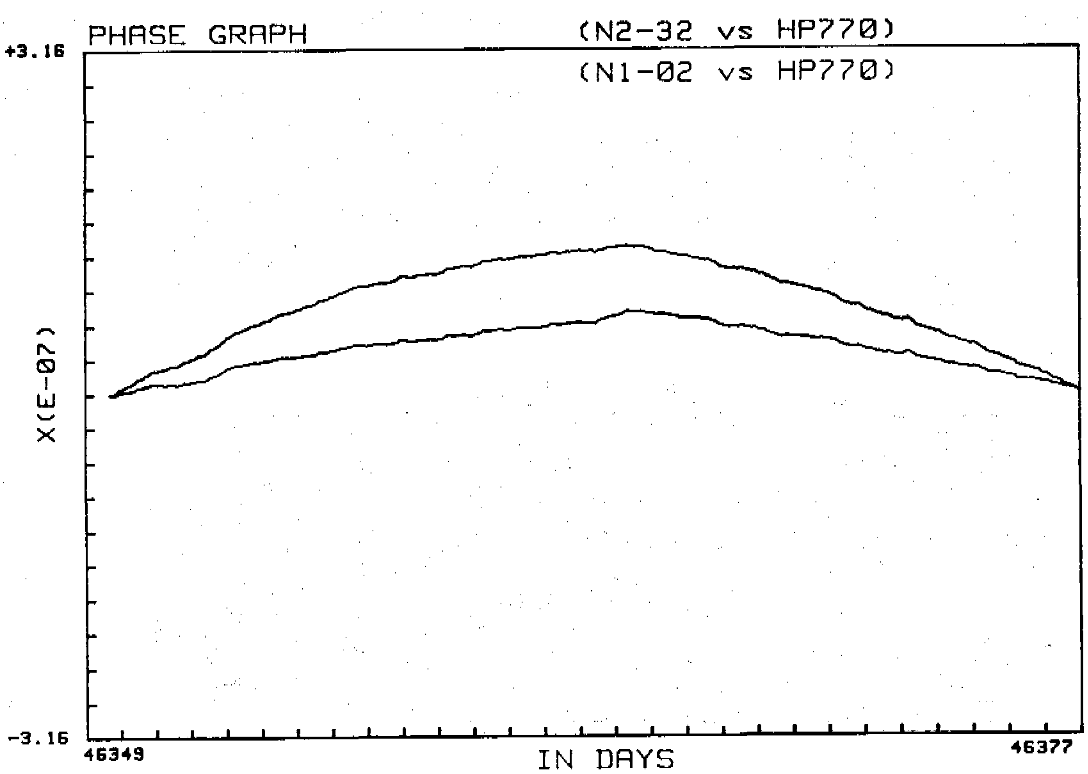
9. N2 vs. P12 Phase noise (100Hz)



10. N2 vs. P12 Phase noise (100kHz)



11. N1 vs N2 Phase Plot



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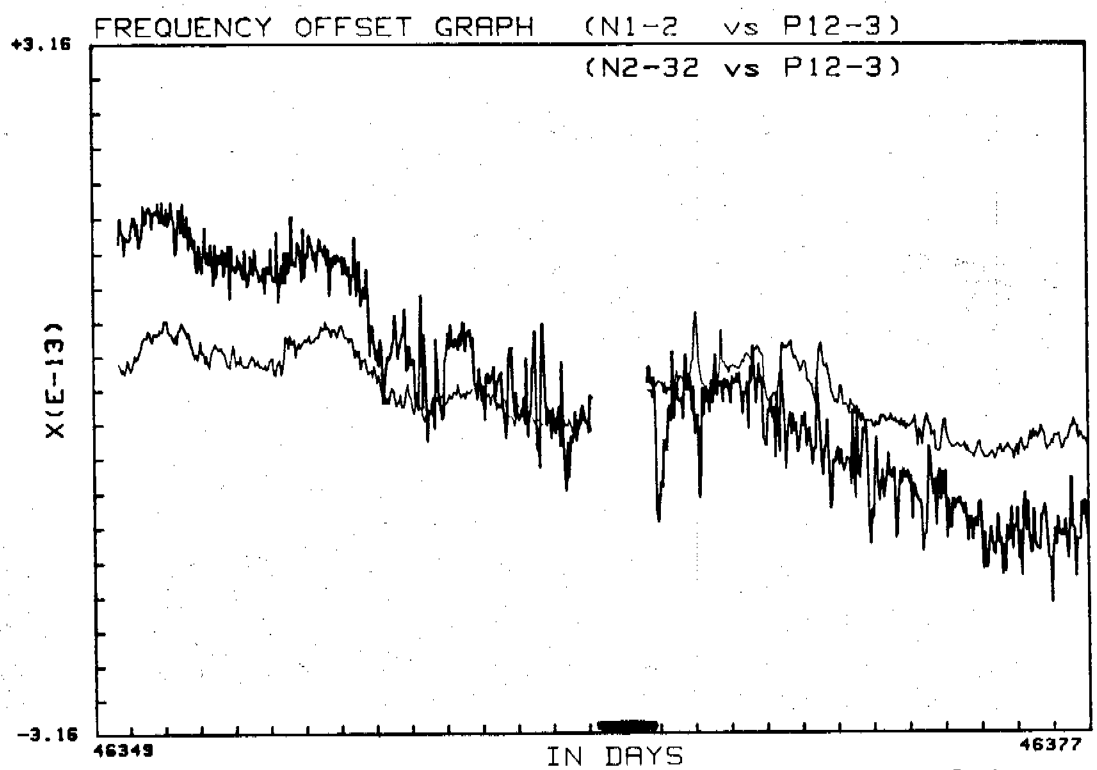
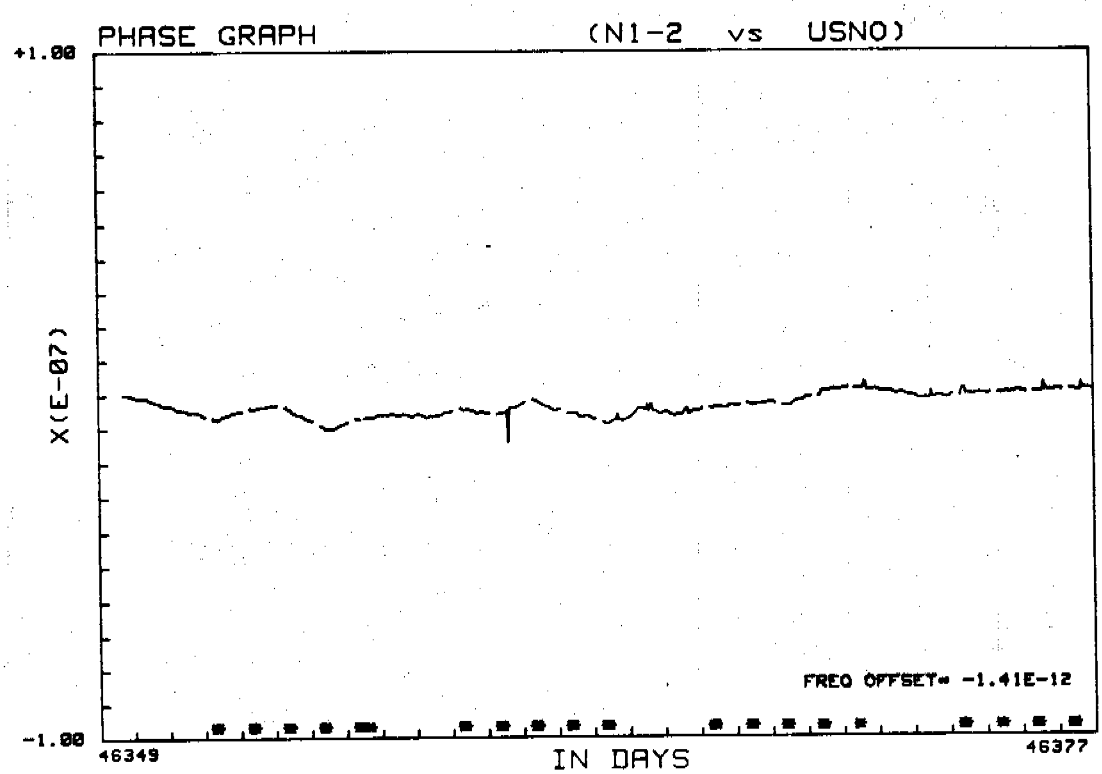
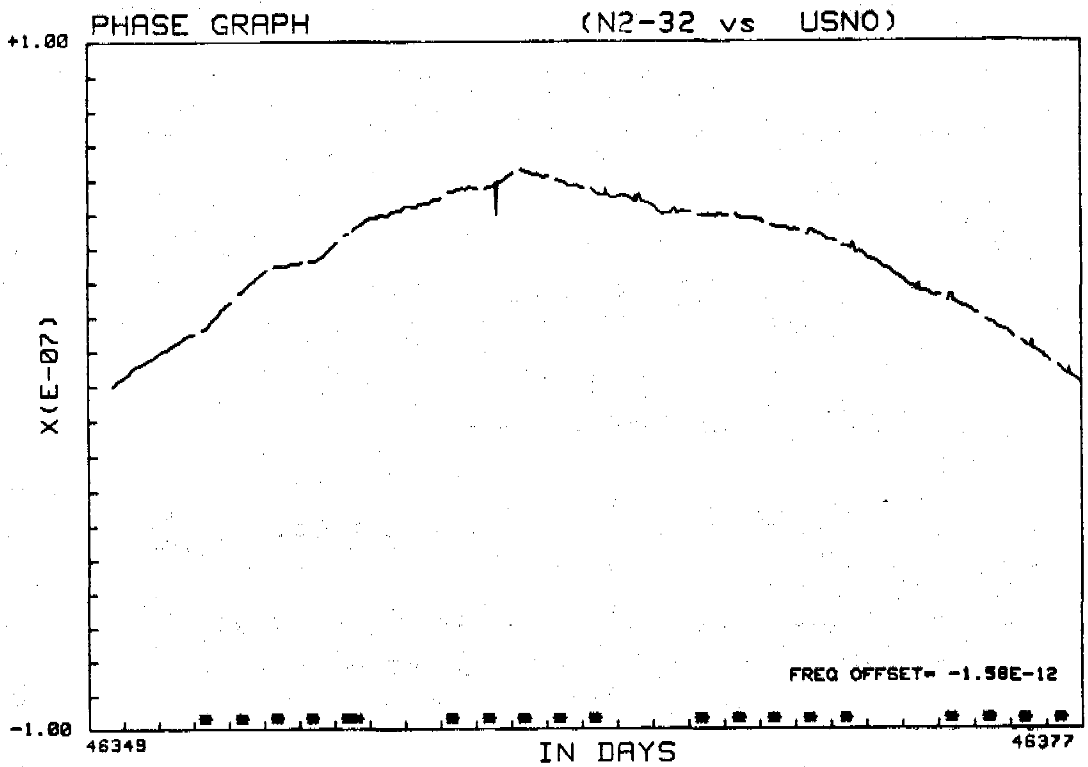


13. N1 and N2 vs P12 Frequency Offset Plot



14. N1 vs. USNO Phase Plot



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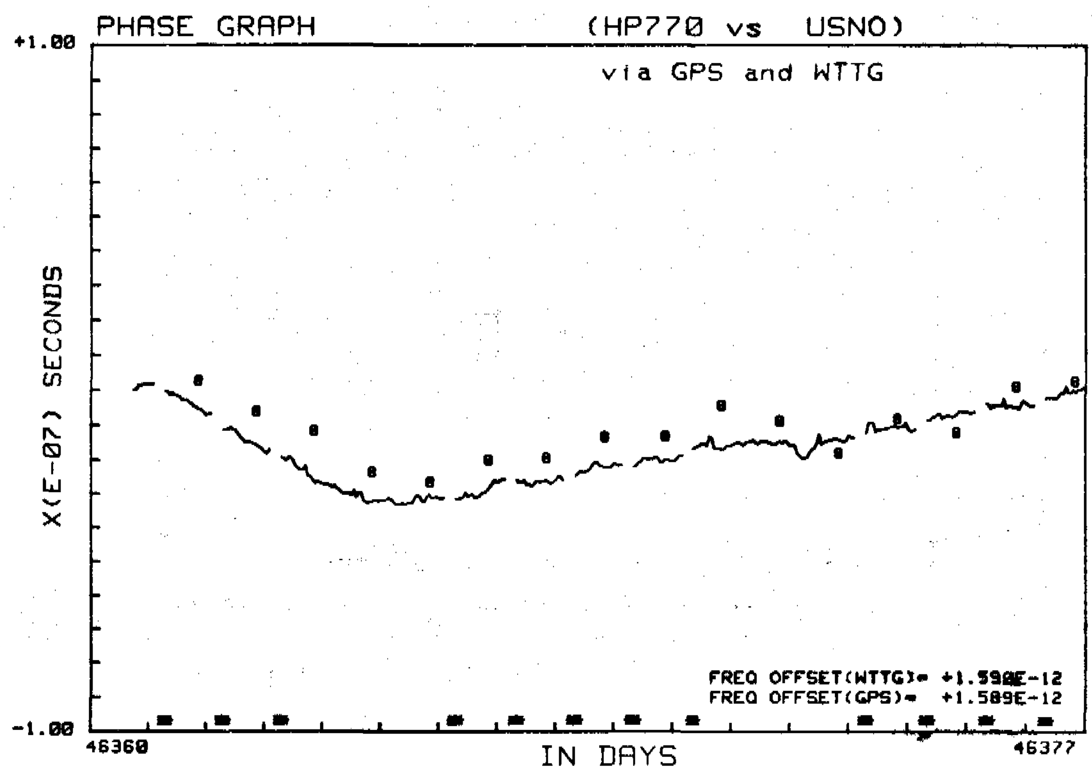
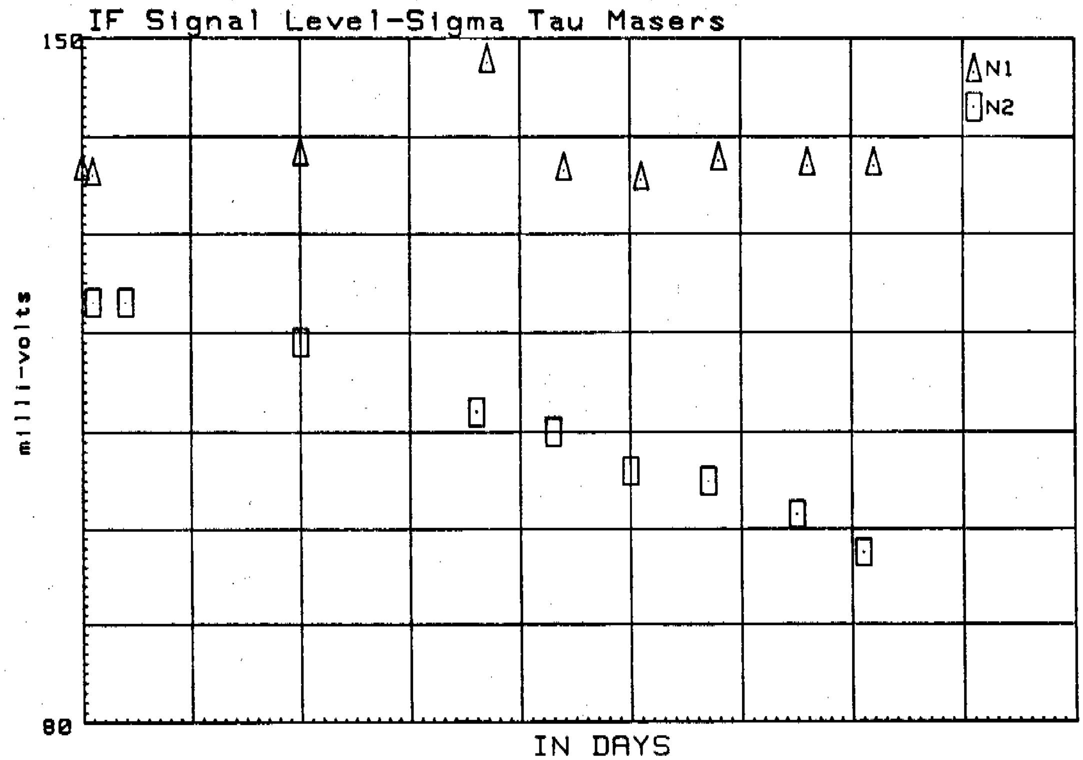
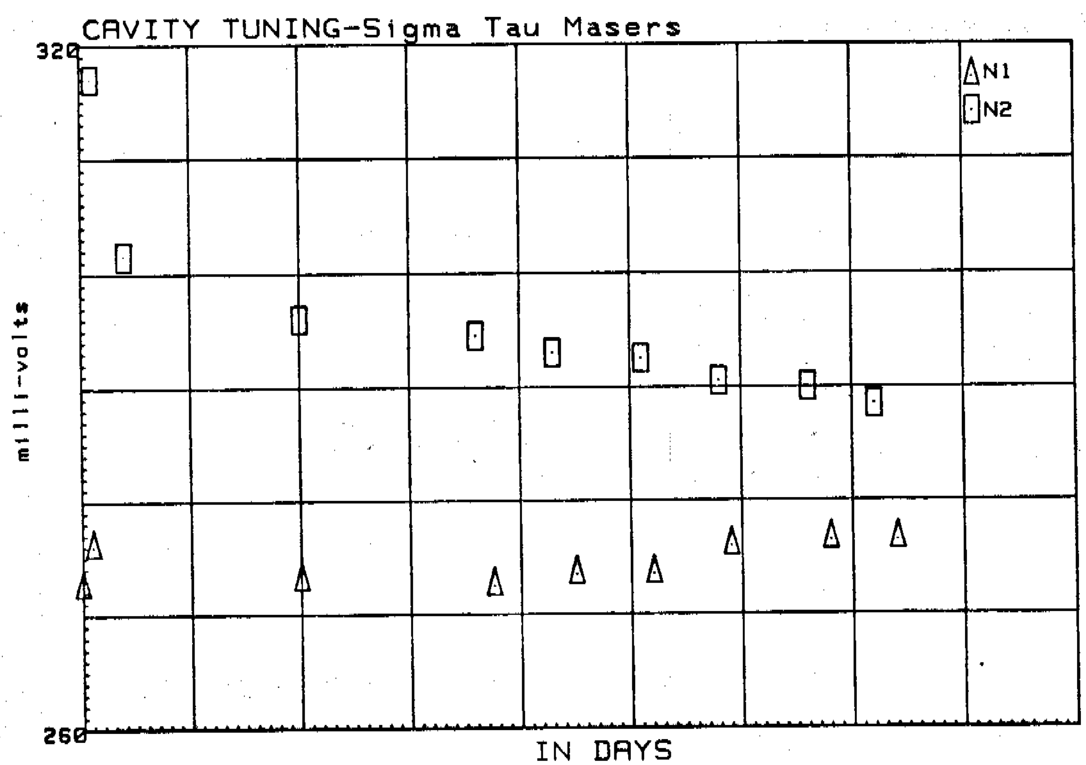


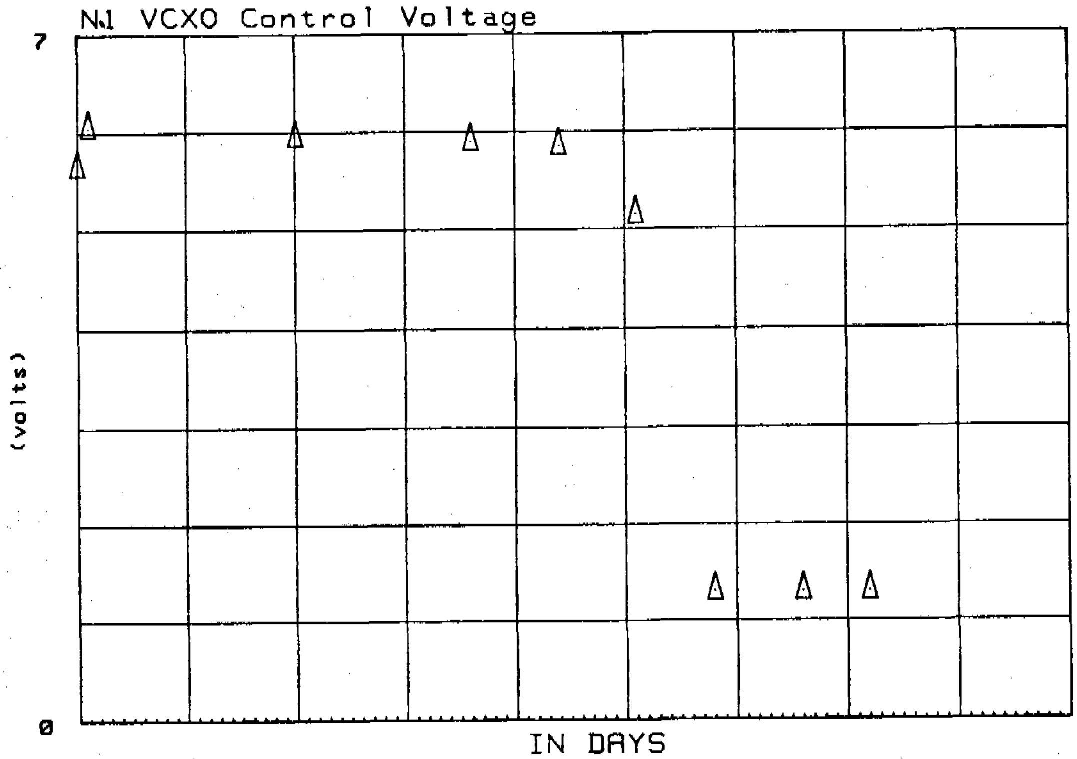
16. CS770 Phase vs. USNO via WTTG and GPS



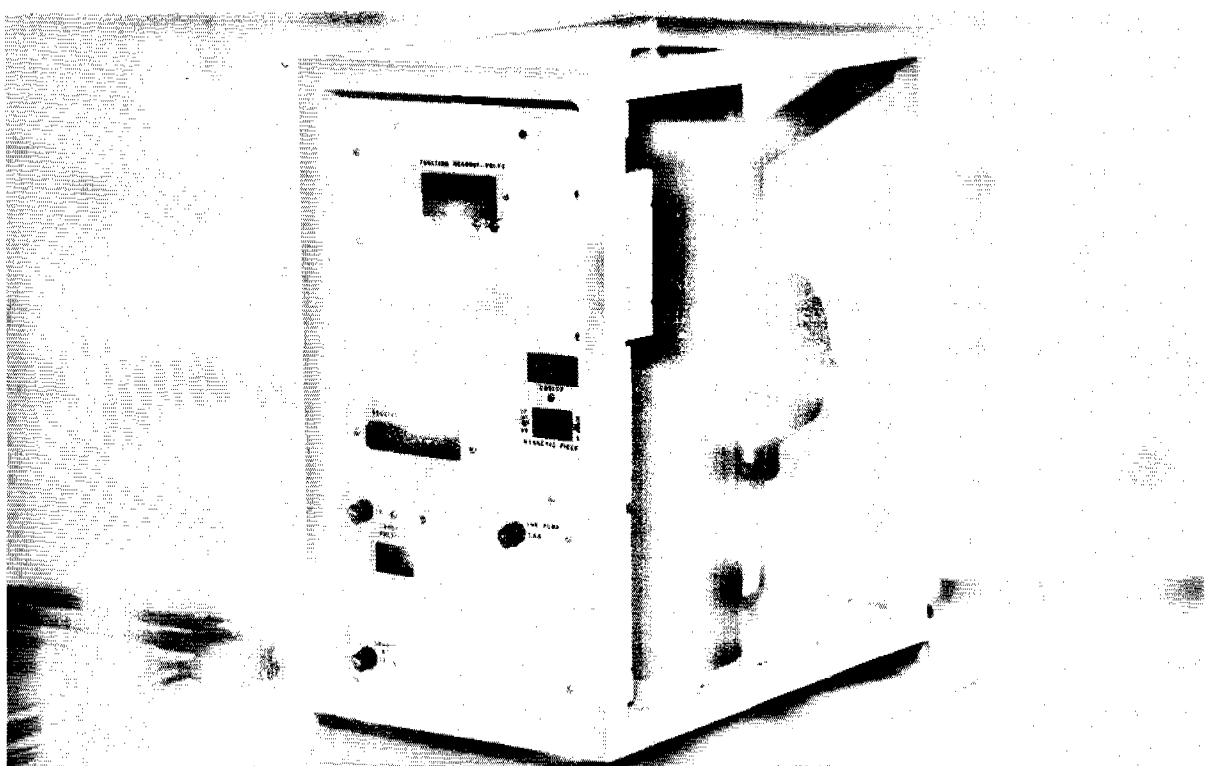
17. Maser IF Level



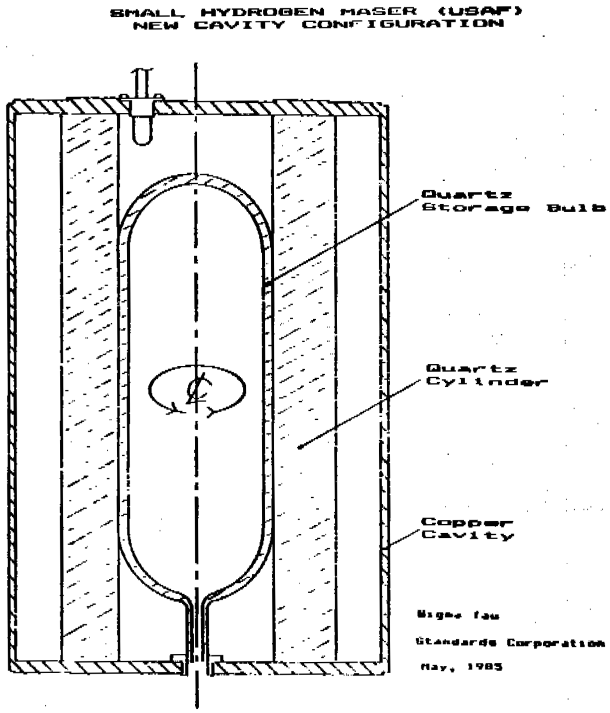
18. Maser Cavity Tuning



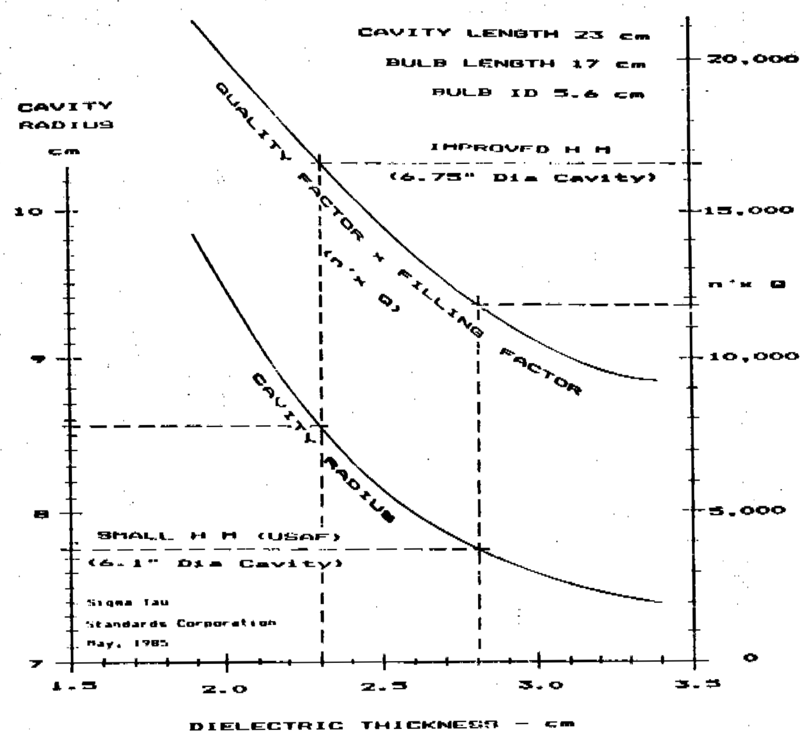
19. N1 VCXO Control Voltage



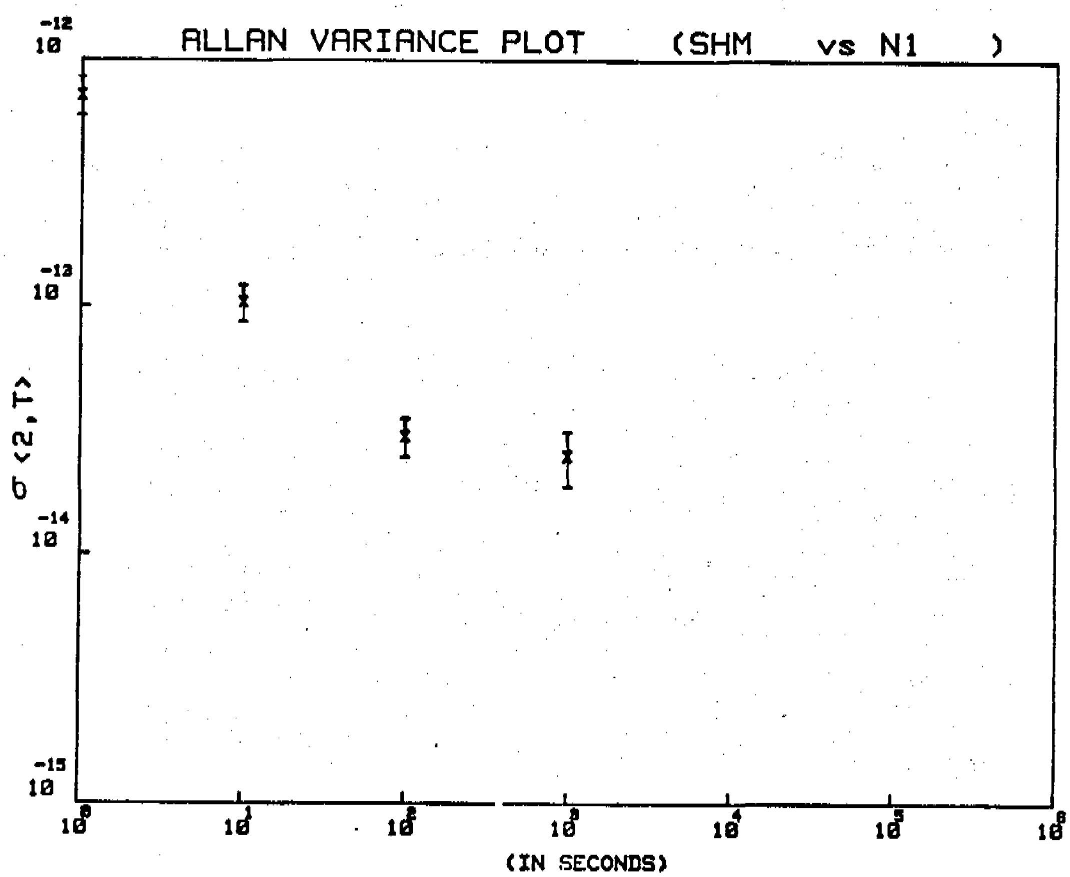
20. Small Hydrogen Maser Photo



21. **Small Hydrogen Maser, New Configuration**



22. **Small Cavity Parameters**



23. Small Maser Test Data

QUESTIONS AND ANSWERS

LAUREN RUEGER, APPLIED PHYSICS LAB., JOHNS HOPKINS UNIVERSITY:
Did you make any measurements of temperature coefficient, or what were the conditions of temperature control when you made the long term tests?

JOE WHITE, NAVAL RESEARCH LABORATORY:
We did this in regular laboratory space and due to the time involved we did not measure detailed temperature coefficients. I have a question for you - do you have measurements on your maser?

MR. RUEGER:
Something on the order of a part in ten to the fourteen per degree C. Do you have knowledge of how much your laboratory varied then?

MR. WHITE:
We did record it. It was typically about two degrees peak to peak, with a few excursions beyond that. That is Celsius.